Modeling Six Degrees of Freedom Rigid-Body Motion of a Thermocapillary Microswimmer

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Abstract

Thermocapillary effect is widely used in microfluidic applications for sensing and actuation [1-4]. Moreover, it has been recently demonstrated that thermocapillary effect can also be used to generate rigid-body motion [5]. Furthermore, it is possible to cast Marangoni flows to achieve controllable rigid-body motion in 3D space. To this effect, here we present the basics of a simulation technique to analyze 6-dof time-dependent rigid-body motion of such a microswimmer actuated with Marangoni effect.

Figure 1 shows the microswimmer designed as rectangular prism with ten individual cubic air pockets embedded on all four sides, confined to cylindrical channel filled with water at room temperature. The microswimmer is 105 µm long and 26.25 µm in depth. The channel is ten times longer than the swimmer to minimize end-effects. Furthermore, the channel diameter is ten times that of the shortest dimension of the microswimmer. Each pocket is 125 µm-cube in volume.
Four physics interfaces are used to govern the overall time-dependent physics in effect: Laminar Flow interface (spf), i.e., full Navier-Stokes equations for incompressible fluids subject to conservation of mass; Heat Transfer in Fluids interface (ht), i.e., full conservation of energy equations subject to Non-Isothermal Flow (nitf) and Marangoni Effect (me) Multiphysics interface; Moving Mesh interface (ale) with rubber-mesh approach [6,7] to handle the mesh deformation within the fluidic domain, Ω(t); and finally the Global ODEs and DAEs interface (ge) in order to introduce the rigid-body kinematics, i.e., velocity vectors V and Ω associated with the 6-dof rigid body translation and rotation, respectively, of the microswimmer. Respective boundary conditions and component couplings are depicted in Figure 1, where the function f(x,y,z) contains spatial information on predefined mesh deformation, which is called the rubber-mesh approach [6,7].

We applied 30 µW heat input on the right-hand-side of the microswimmer, which resulted in a temperature gradient throughout its surface. This temperature gradient induced local flow fields near the air pockets thus exerting shear force on nearby surfaces. Figure 2(a) illustrates the mesh deformation on the stationary and moving surfaces; Figure 2(b) depicts the streamlines induced around the microswimmer due to Marangoni effect; Figure 2(c) shows the temperature profile in the channel with planes in different locations; and Figure 2(d) shows the rigid body rotation velocities. Complex rotation calculations are carried out by quaternion rotations [8]. Moreover, the forward velocity is found to be almost one body-length at the end of 1-second-simulation.

We simulated the time-dependent behavior of a microswimmer actuated by Marangoni effect. We imposed a constant heat input on one half of the swimmer, generating a temperature profile along the surfaces which in turn invoked the thermocapillary flow at the interfaces between trapped air pockets and the surrounding water. Resultant overall flow field generated the necessary thrust in order to move forward. We also observed that with rubber mesh approach and quaternion rotation formulae the total degrees of freedom to solve for reduces considerably (around 70K), hence reducing computational requirements and solution time (approximately half an hour).

Reference

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Figures used in the abstract

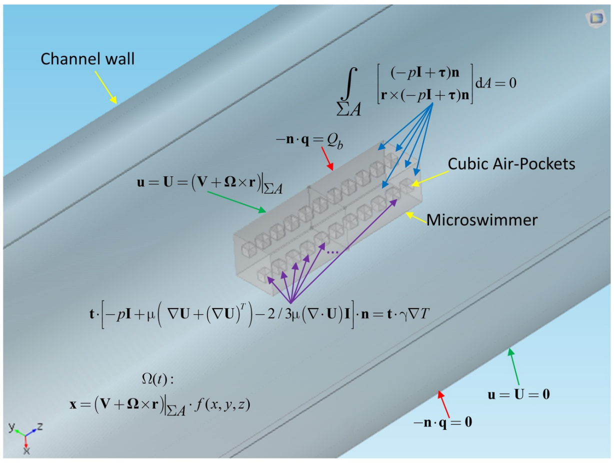

Figure 1: Microswimmer confined to the cylindrical micro-channel. Geometric entities are indicated with yellow arrows. Boundary condition arrows pertaining to; ‘Laminar Flow’ and ‘Moving Mesh’ are in green ‘Heat Transfer in Fluids’ are in red, ‘Marangoni Effect’ are in purple, and ‘Global ODEs and DAEs’ subject to integration component couplings are in blue.

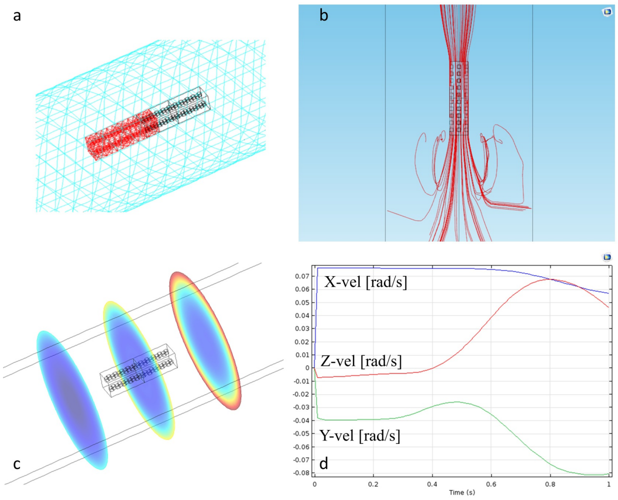

Figure 2: Results of the simulation: rigid-body displacement of the microswimmer (a); streamlines around the microswimmer (b); temperature profile in the channel (c); rigid-body rotation velocities of the microswimmer (d).